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The Tevatron Higgs exclusion limits and theoretical uncertainties: a critical appraisal

J. Baglio[1], A. Djouadi[1,2], S. Ferrag[3], R.M. Godbole[2,4]

[1] Laboratoire de Physique Théorique, U. Paris–Sud and CNRS, F–91405 Orsay, France.
[2] Theory Unit, Department of Physics, CERN, CH-1211 Geneva 23, Switzerland.
[3] Dpt. of Physics and Astronomy, U. of Glasgow, G12 8QQ Glasgow, United Kingdom.
[4] Center for High Energy Physics, Indian Institute of Science, Bangalore 560 012, India.

Abstract

We examine the exclusion limits set by the CDF and D0 experiments on the Standard Model Higgs boson mass from their searches at the Tevatron in the light of large theoretical uncertainties on the signal and background cross sections. We show that when these uncertainties are consistently taken into account, the sensitivity of the experiments becomes significantly lower and the currently excluded mass range $M_H = 158$–175 GeV could be entirely reopened. The necessary luminosity required to recover the current sensitivity is found to be a factor of two higher than the present one.

With its successful operation in the last years, the Fermilab Tevatron $p\bar{p}$ collider has now collected a substantial amount of integrated luminosity which allows the CDF and D0 experiments to be sensitive to the Higgs particle, the remnant of the mechanism that breaks the electroweak gauge symmetry of the Standard Model (SM) and is at the origin of elementary particle masses [1, 2].

At the Tevatron, the main search channel for the SM Higgs boson is the top and bottom quark loop mediated gluon–gluon fusion mechanism $gg \to H$ with the Higgs boson decaying into WW pairs which lead to the clean $\ell\nu\ell\bar{\nu}$ final states with $\ell = e, \mu$. The subleading Higgs–strahlung processes $q\bar{q} \to WH, ZH$ add a little to the sensitivity, in particular at low Higgs masses. Strong constraints beyond the well established LEP bounds [3] have been recently set by the CDF and D0 collaborations on the Higgs mass and the range $M_H = 158$–175 GeV has been excluded at the 95% confidence level (CL) [4].

Nevertheless, this exclusion limit relies crucially on the theoretical predictions for the cross sections of both the Higgs signal and the relevant SM backgrounds which, as is well known, are affected by significant uncertainties. In a recent study [5], it has been re-emphasized that this is indeed the case for the main Higgs search channel at the Tevatron: adding all sources of theoretical uncertainties in a consistent manner, one obtains an overall uncertainty of about $\pm 40\%$ on the $gg \to H \to \ell\nu\ell\bar{\nu}$ signal[1]. This is much larger than the uncertainty assumed in the CDF/D0 analysis, i.e. 10% for D0 and 20% for CDF, thus casting some doubts on the resulting exclusion limit.

In this letter, we confront the Tevatron exclusion Higgs limit with the theoretical uncertainties that affect the signal and background rates. We show that when they are included, the sensitivity of the the CDF/D0 experiments is significantly lower than the currently quoted one. We estimate the necessary luminosity that is required to recover the current sensitivities and find that it should be higher than the present luminosity by a factor up to two.

We begin our investigation by summarizing the impact of the theoretical uncertainties on the $gg \to H$ signal cross section which has a threefold problem. First, the perturbative QCD corrections to the cross section turned out to be extremely large: the K–factor defined as the ratio of the higher order to the leading order (LO) [7] cross sections, is about a factor of two at next-to-leading order (NLO) [8] and about a factor of three at the next-to-next-to-leading order (NNLO) [9]. It is clear that it is this exceptionally large K–factor which allows a sensitivity to the Higgs boson at the Tevatron with the presently collected data. Nevertheless, the K–factor is so large that one may question the reliability of the perturbative series. As a corollary, the possibility of still large higher order contributions beyond NNLO cannot be excluded.

It has become customary to estimate the effects of these yet uncalculated higher order contributions from the variation of the cross section with the (renormalisation μ_R and factorisation μ_F) scale at which the process is evaluated. Starting from a median scale μ_0 which is taken to be $\mu_R = \mu_F = \mu_0 = \frac{1}{2} M_H$ in the $gg \to H$ process, the current convention

[1]There are also uncertainties on the Higgs decay branching ratios, but they are very small in the excluded M_H range; see Ref. [6].

is to vary these two scales within the range $\mu_0/\kappa \le \mu_R, \mu_F \le \kappa\mu_0$ with the constant factor chosen to be $\kappa = 2$. However, as the QCD corrections are so large in the present case, it is wise to extend the domain of scale variation and adopt instead a value $\kappa = 3$. This is the choice made in Ref. [5] which resulted in an $\mathcal{O}(20\%)$ scale uncertainty[2] on $\sigma^{\rm NNLO}_{gg\to H}$.

Another problem that is specific to the $gg \to H$ process is that, already at LO, it occurs at the one–loop level with the additional complication of having to account for the finite mass of the loop particle. This renders the NLO calculation extremely complicated and the NNLO calculation a formidable task. Luckily, one can work in an effective field theory (EFT) approach in which the heavy loop particles are integrated out, making the calculation of the contributions beyond NLO possible. While this approach is justified for the dominant top quark contribution for $M_H \lesssim 2m_t$, it is not valid for the b-quark loop and for those involving the electroweak gauge bosons [11]. The uncertainties induced by the use of the EFT approach at NNLO are estimated to be of $\mathcal{O}(5\%)$ [5].

A third problem is due to the presently not satisfactory determination of the parton distribution functions (PDFs). Indeed, in this process which is initiated by gg fusion, the gluon densities are poorly constrained, in particular in the high Bjorken–x regime which is relevant for Higgs production at the Tevatron. Furthermore, since the $gg \to H$ cross section is proportional to α_s^2 at LO and receives large contributions at $\mathcal{O}(\ge \alpha_s^3)$, a small change of α_s leads to a large variation of $\sigma^{\rm NNLO}_{gg\to H}$. Related to that is the significant difference between the world average α_s value and the one from deep-inelastic scattering (DIS) data used in the PDFs [12].

Modern PDF sets provide a method to estimate these uncertainties by allowing a 1σ (or more) excursion of the experimental data that are used to perform the global fits. In addition, the MSTW collaboration [13] provides a scheme that allows for a combined evaluation of the PDF uncertainties and the (experimental and theoretical) ones on α_s. In Ref. [5], the combined 90% CL PDF+$\Delta^{\rm exp}\alpha_s + \Delta^{\rm th}\alpha_s$ uncertainty on $\sigma^{\rm NNLO}_{gg\to H}$ at the Tevatron, was found to be of order 15%. However, this (Hessian) method does not account for the theoretical assumptions that enter into the parametrization of the PDFs. A way to access this theoretical uncertainty is to compare the results for the central values of the cross section with the best–fit PDFs when using different parameterizations.

In Fig. 1, displayed are the values of $\sigma^{\rm NNLO}_{gg\to H}$ obtained when using the gluon densities that are predicted by the four PDF sets[3] that have parameterizations at NNLO: MSTW [13], JR [14], ABKM [15] and HERAPDF [16]. In the later case, two sets are provided: one with an α_s value that is close to that of MSTW and another one with the α_s that is obtained using DIS data alone. As can be seen, there is a very large spread in the four predictions, in particular at large M_H values where the poorly constrained gluon densities at high–x are involved. The largest rate is obtained with MSTW, but the cross section using the HERAPDF set[4] with the small α_s value is $\approx$40% lower for $M_H \approx 160$ GeV.

[2]See also Ref. [10] for another reason to increase the scale uncertainty to 20%.

[3]We consider only NNLO PDFs as we make the choice of using partonic cross sections and PDFs that are consistently taken at the same order of perturbation theory.

[4]It is often argued against the HERAPDF scheme, which uses consistently only HERA data to determine the flavour decomposition, that it does not use any jet (Tevatron or DIS) data which is in principle

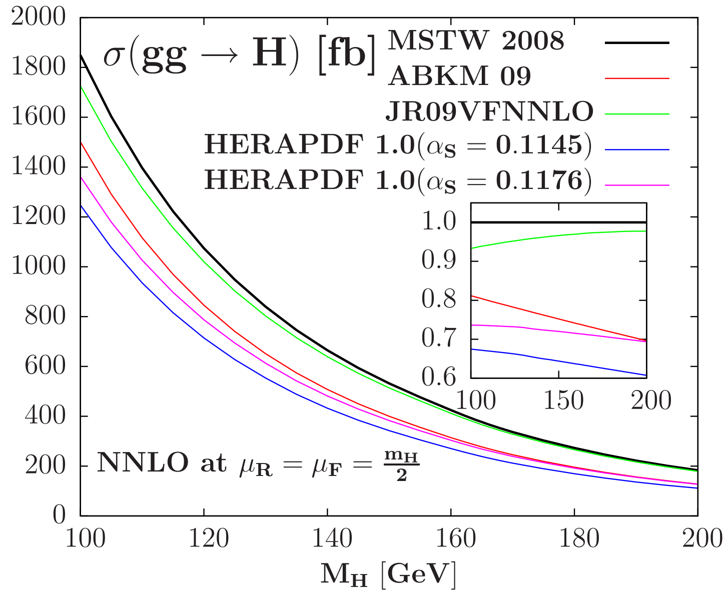

Figure 1: The $gg \to H$ cross section as a function of M_H when the four NNLO PDF sets, MSTW, ABKM, JR and HERAPDF, are used. In the inserts, shown are the deviations with respect to the central MSTW value.

A related issue, which is of utmost importance, is the way these various uncertainties should be combined. The CDF and D0 experiments simply add in quadrature the uncertainties from the scale variation and the PDF uncertainties obtained through the Hessian method (and ignore the smaller EFT uncertainty) and they obtain an overall uncertainty of order 20% on the inclusive cross section. We believe (see also Ref. [18]) that this procedure has no justification[5]. Indeed, the uncertainties associated to the PDFs in a given scheme should be viewed as purely theoretical uncertainties (due to the theoretical assumptions in the parameterization) despite of the fact that they are presented as the 1σ or more departure from the central values of the data included in the PDF fits. In some sense, they should be equivalent to the spread that one observes when comparing different parameterizations of the PDFs. Thus, the PDF uncertainties should be considered as having no statistical ground (or a flat prior in statistical language), and thus, combined linearly with the uncertainties from the scale variation and the EFT approach, which are pure theoretical errors. This is the procedure recommended, for instance, by the LHC Higgs cross section working group [19]. Another, almost equivalent, procedure has been proposed in Ref. [5]: one applies the combined PDF–α_s uncertainties directly

important in the determination of the gluon densities. However, HERAPDF describes well not only the Tevatron jet data but also the W, Z data. Since this is a prediction beyond leading order, it has also the contributions of the gluon included. This gives an indirect test that the gluon densities are predicted in a satisfactory way. See also Ref. [17].

[5]There were some responses to the addendum of Ref. [5] from CDF and D0 on the `tevnphwg.fnal.gov` web site. While many comments were made on secondary and/or agreed points, the main issue (which explains the difference between our results) is the way to combine the scale and PDF uncertainties, and it was not really addressed.

on the maximal/minimal cross sections with respect to scale variation[6], and then adds linearly the small uncertainty from the EFT approach. This last procedure, that we have used here, provides an overall uncertainty that is similar (but slightly smaller) to that obtained with the linear sum of all uncertainties.

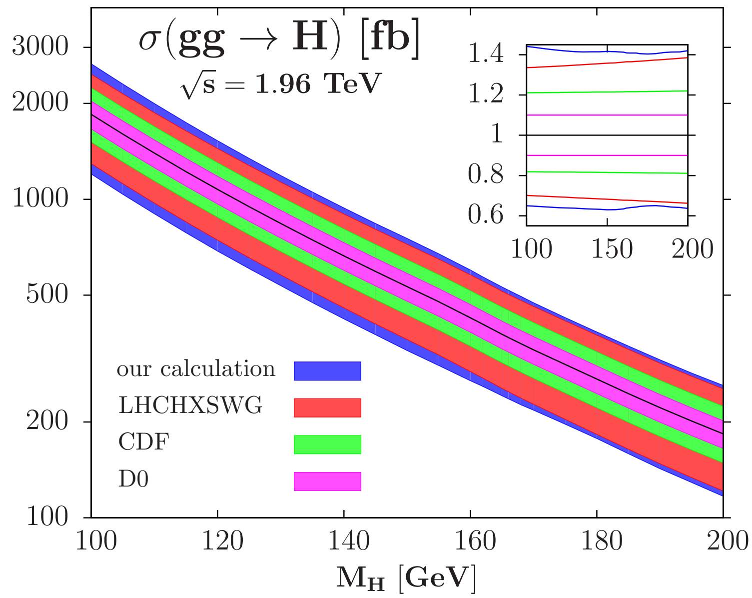

Figure 2: The production cross section $\sigma^{\rm NNLO}_{gg\to H}$ at the Tevatron using the MSTW PDFs, with the uncertainty band when all theoretical uncertainties are added as in Ref. [5] (BD). It is compared the uncertainties quoted by the CDF and D0 experiments [4] as well as the uncertainty when the LHC procedure [19] is adopted. In the insert, the relative size of the uncertainties compared to the central value are shown.

The overall theoretical uncertainty on $\sigma^{\rm NNLO}_{gg\to H}$ that is obtained this way, using MSTW PDFs, is shown in Fig. 2. In the mass range $M_H \approx 160$ GeV with almost the best sensitivity, one obtains a $\approx +41\%, -37\%$ total uncertainty, to be compared to the $\approx 10\%$ and $\approx 20\%$ uncertainties assumed, respectively, by the CDF and D0 collaborations. We also show for comparison, the result obtained when one adds linearly, i.e. as recommended by the LHC Higgs cross section working group, the uncertainties from scale (+20%,–17% on the sum of the jet cross sections[7] and PDFs (+16%, −15% when the MSTW 68%CL PDF+$\Delta^{\rm exp}\alpha_s$ error is multiplied by a factor of two following the PDF4LHC recommendation), leading to a total of $\approx$+36%,–32% for $M_H \approx 160$ GeV. Thus, the uncertainty that we assume is comparable to the one obtained using the LHC procedure [19], the difference being simply due to the additional $\mathcal{O}(5\%)$ uncertainty from the use of the EFT approach that we also include.

[6] A similar procedure has also been advocated in Ref. [20] for top quark pair production.

[7] An additional uncertainty of $\approx$7.5% from jet acceptance is introduced when considering the Higgs+jet cross sections. We will consider it to be experimental and, when added in quadrature to others, will have little impact.

Let us stress again that the comparison between our values and those assumed by the experimental collaborations becomes even worse when the cross section is evaluated with another set of PDFs. For instance, with the HERA PDF parametrization, there is a reduction of $\approx 40\%$ of the normalisation compared to the central value adopted in the CDF/D0 combined analysis.

Thus if the $\approx 20\%$ total uncertainty assumed by the CDF collaboration is adopted, one can consider two scenarios. The first one is a reduction of $\sigma^{\rm NNLO}_{gg\to H}$ by $\approx 20\%$ to account for the difference between the quadratic and (almost) linear ways of combining the individual uncertainties. A second scenario, would be simply to adopt the normalisation obtained using the HERA PDFs which gives a $\approx 40\%$ reduction of $\sigma^{\rm NNLO}_{gg\to H}$. In both cases, the remaining $\approx 20\%$ uncertainty due to scale variation and the EFT will correspond to the overall theoretical uncertainty that has been assumed in the Tevatron analysis.

So far, we have only addressed the issue of the signal rate. However, it is clear that one should equally consider the same uncertainties in the background cross sections. The by far largest background is $p\bar{p}\to W^+W^-$ for which CDF/D0 assume the inclusive cross section to be $\sigma = 11.34^{+4.9\%}_{-4.3\%}({\rm scale})^{+3.1\%}_{-2.5\%}({\rm PDF})$ pb. We have reevaluated the rate using `MCFM` [21] and find $\sigma = 11.55^{+5\%}_{-6\%}({\rm scale})^{+5\%}_{-8\%}(90\%{\rm CL\,PDF})$ pb using the MSTW scheme (the errors due to α_s are negligible here) which gives $\sigma = 11.55^{+11\%}_{-14\%}$ pb if the errors are added according to Ref. [5]. In fact, if we adopt the ABKM or HERAPDF sets, we would obtain a rate of, respectively, 12.35 pb and 11.81 pb. i.e $\approx 9\%$ higher in the maximal case. We will thus consider that $\sigma(p\bar{p}\to W^+W^-)$ can be $\approx 10\%$ larger/lower than assumed by CDF/D0[8] and we will consider a third scenario in which the normalization of the $p\bar{p}\to WW$ background is changed by $\pm 10\%$.

Let us now come to the discussion of the Higgs Tevatron exclusion limit in the light of these theoretical uncertainties. We will base our exploration on the CDF study published in Ref. [22] which provides us with all the necessary details. In the analysis of the $gg\to H\to WW\to \ell\ell\nu\nu$ signal, the production cross section has been broken into the three pieces which yield different final state signal topologies, namely $\ell\ell\nu\nu$+0 jet, $\ell\ell\nu\nu$+1 jet and $\ell\ell\nu\nu$+2 jets or more. These channels which represent, respectively, $\approx 60\%$, $\approx 30\%$ and $\approx 10\%$ of the total $\sigma^{\rm NNLO}_{gg\to H}$ [18], have been studied separately. In the $\ell\ell\nu\nu$+0 jet and +1 jet samples, two configurations have been analyzed, one with a high and one with a low signal over background ratio (depending on the quality of the lepton identification). In addition, a sample with a low invariant mass for the two leptons, $M_{\ell\ell}\leq 16$ GeV, has been included. Five additional channels resulting from the contributions of the Higgs–strahlung processes are also included: $p\bar{p}\to VH\to VWW$ leading to same sign dilepton and to trilepton final states. These channels give rather small signal rates, though.

Our main goal is to estimate the necessary relative variation of the integrated luminos-

[8] We have also evaluated $\sigma(p\bar{p}\to t\bar{t})$ under the same assumptions as [4] but with $m_t = 173.3\pm 1.1$GeV and find $\sigma(p\bar{p}\to t\bar{t}) = 7.07^{+7.6\%}_{-8.6\%}({\rm scale})^{+10.5\%}_{-8.0\%}({\rm PDF}+\Delta^{\rm exp+th}\alpha_s)\pm 3.3\%(\Delta m_t)$ pb, which leads using the procedure of [5] to a total uncertainty of $\Delta\sigma/\sigma = ^{+15.6\%}_{-14.6\%}$, i.e much larger than the one assumed by CDF and D0. In the case of the Drell–Yan process, there is also a $\approx 10\%$ excess in the rate if one uses HERAPDF instead of the MSTW set: $\sigma^{\rm HERA}_{p\bar{p}\to Z} = 7.6$ nb versus $\sigma^{\rm MSTW}_{p\bar{p}\to Z} = 7$ nb [17].

ity needed to reproduce the currently quoted sensitivity of the CDF collaboration, if the normalization of the Higgs signal cross section (as well as the corresponding backgrounds) is different from the one assumed to obtain the results.

Our approach consists of the following. First, we try to reproduce as closely as possible the CDF results using the information given in Ref. [22] for a mass $M_H = 160$ GeV, for which the sensitivity is almost the best (we will assume that the results are similar in the entire excluded mass range $M_H \approx 158$–175 GeV). Then, we consider the two scenarios discussed previously which, in practice, *reduce the normalisation* of the Higgs production cross section by $\approx 20\%$ (when all the uncertainties are added using the procedure of Ref. [5]) and $\approx 40\%$ (when the HERAPDF set is used to derive the central value of the cross section). We estimate the *relative variation* of the sensitivity and increase the integrated luminosity until we recover our initial sensitivity. Finally, we assume that the obtained relative variations of the sensitivity as well as the required luminosity to reproduce the initial sensitivity, would be the same for the CDF experiment.

A naive attempt to reproduce the CDF results [22] was to use the background, signal and data numbers for all the search channels of Tables I–VIII without including the neural-network information or any treatment that uses shape information. This naive approach resulted in a sensitivity (95% CL/$\sigma_{\rm SM}$) ≈ 12 times weaker than the CDF one. This large difference made us feel uncomfortable, as we would have needed to make the above assumptions over one order of magnitude difference for the sensitivity (or two orders of magnitude for the resulting necessary luminosity) compared to the CDF analysis[9].

To be as close as possible to the CDF analysis and results [22], we considered their neural network outputs for the 10 search channels (each one for the signals, backgrounds and data) presented in Figs. 2,4,$\cdots$,16 to build the background only and the background plus signal hypotheses, implemented them in the program `MClimit` [23] and used a ratio of log–likelihood "à la LEP" as a test–statistic for which we combined the above channels; this provided the 95%CL/$\sigma_{\rm SM}$ sensitivity limit on the Higgs boson at the considered mass of $M_H = 160$ GeV. A median expected 95%CL/$\sigma_{\rm SM}$ limit of $S_0 = 1.35$ has been obtained, to be compared to $S_0 = 1.05$ in the CDF analysis; for the observed 95%CL/$\sigma_{\rm SM}$ limit, the agreement is better as we obtain 1.35 compared to 1.32. We feel thus satisfied with this rather close result as even the CDF and D0 collaborations agree in their methods within only 10% accuracy for the same input Monte Carlo and data [24]. We therefore believe that we can safely adopt the three working hypotheses described above.

We consider the first two scenarios in which the $gg \to H \to WW \to \ell\ell\nu\nu$ signal cross section has been reduced by 20% and 40%. In each case, the expected signals and the corresponding backgrounds at the Tevatron have been multiplied by a luminosity factor that has been varied. For each value of the luminosity factor, the corresponding median expected 95%CL/$\sigma_{\rm SM}$ has been estimated and normalized to the initial sensitivity $S_0 =$ 1.35 obtained above. The results are reported in Fig. 3 where the Tevatron luminosity is shown as a function of the obtained normalised sensitivity. The luminosity needed to

[9]This factor ≈ 12 gain in sensitivity obtained using neural network techniques (including spin–correlations, the main discriminant), is to be compared with the modest gain of ≈ 30–50% envisaged by the LHC experiments. It turned, though, that the CDF cut–based analysis was not fully optimised.

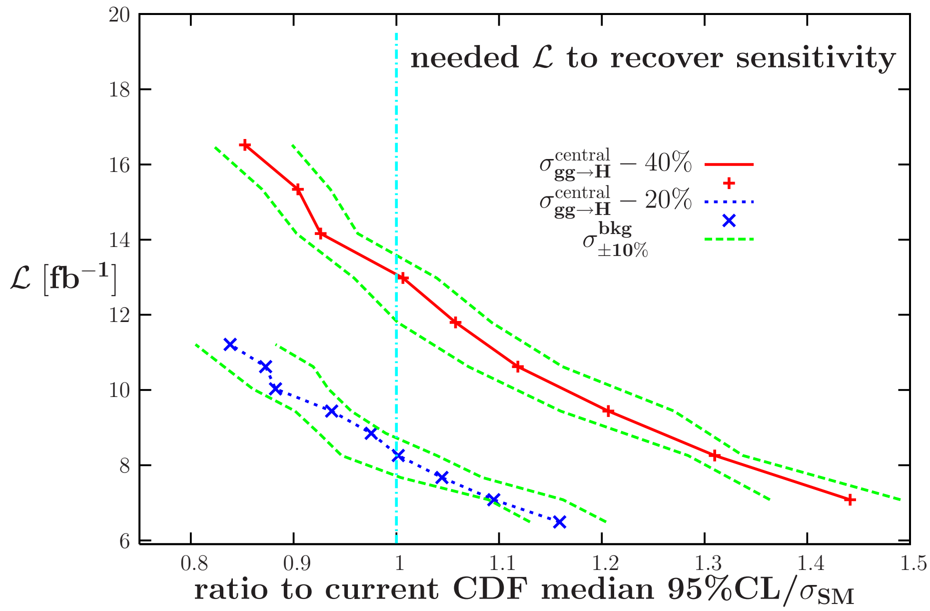

Figure 3: The luminosity needed by the CDF experiment to recover the current sensitivity (with 5.9 fb^{-1} data) when the $gg \to H \to \ell\ell\nu\nu$ signal rate is lowered by 20 and 40% and with a $\pm 10\%$ change in the $p\bar{p} \to WW$ dominant background.

recover the current S_0 CDF sensitivity is given by the intersection of the vertical (blue) line with the luminosity curves. One sees that if $\sigma^{\rm NNLO}_{gg\to H}$ is lowered by 20%, a luminosity of ≈ 8 fb^{-1}, compared to 5.9 fb^{-1} used in [22] would be required for the same analysis to obtain the current sensitivity. If the rate is lower by 40%, the required luminosity should increase to ≈ 13 fb^{-1}, i.e. more than a factor of two, to obtain the present CDF sensitivity.

As an additional exercise, we also analyzed the impact of changing the normalization of the background cross sections by $\pm 10\%$, as in our third scenario, simultaneously with lowering the signal[10] by 20 and 40%. One sees that increasing/decreasing the background will degrade/improve the sensitivity and a $\approx 10\%$ higher/lower luminosity would be required to recover the sensitivity.

We conclude by noting that the reduction of the signal by 40% as would be the case if the HERAPDFs were used for its normalization, would reopen the entire mass range $M_H = 158$–175 GeV excluded by the CDF/D0 analysis with 12.6 fb^{-1} combined data. Hence, we face the uncomfortable situation in which the Higgs exclusion limit depends on the considered PDF.

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[10]The correlation between signal and background is implicitly taken into account as we use the results of [22]; we assume though that it is almost the same when another PDF set is adopted for both signal and background.

Erratum

After our paper had appeared in Physics Letters B, we realised that an error occurred in the numerical analysis which had led to Fig. 1 for the $gg \to H$ production cross section when the four NNLO PDF sets are adopted. In the plot with the two HERAPDF sets, the central scales at which $\sigma^{\rm NNLO}_{gg\to H}$ has been evaluated were not set to $\mu_R = \mu_F = \frac{1}{2}M_H$ as it should have been, but at $\mu_R = \mu_F = \frac{3}{2}M_H$ which gives the minimal cross section once the scale uncertainty is included. This explains the large difference in the cross section[11], up to 40%, between the MSTW and HERAPDF predictions. We thus present our *mea culpa* and produce in Fig. 4 the correct figure where all scales are consistently set to $\mu_R = \mu_F = \frac{1}{2}M_H$. The difference between the MSTW and HERAPDF predictions reduces now to $\approx$ 20% at most, which is indeed much more reasonable. In this case, the smallest value of the cross section is given when using the ABKM set and amounts to $\approx$ 20%–30% in the considered Higgs mass range as noticed in Ref. [5] (this difference is slightly larger if the new ABM10 PDF set is used [17]). Note that the same analysis presented for the LHC in Ref. [6] is not affected by this problem.

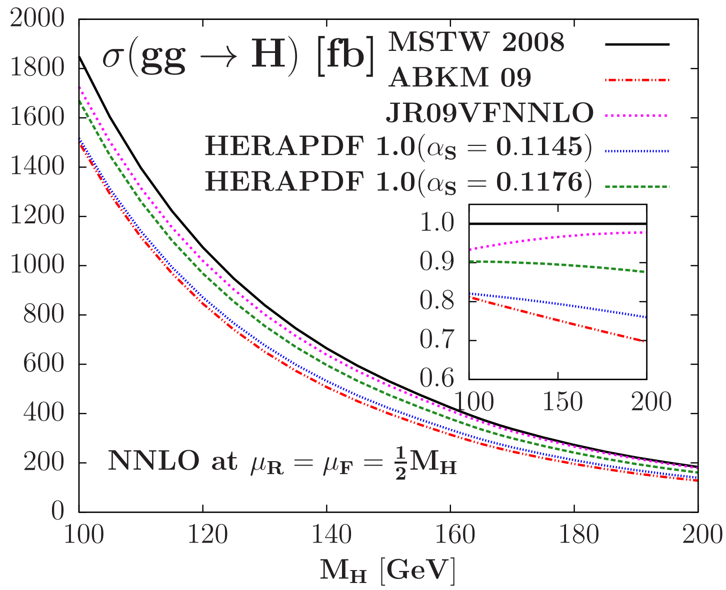

Figure 4: The $gg \to H$ cross section as a function of M_H when the four NNLO PDF sets, MSTW, ABKM, JR and HERAPDF, are used. In the inserts, shown are the deviations with respect to the central MSTW value.

This error does not affect the subsequent discussion and almost does not change our conclusions. Indeed, the main analysis which led to Fig. 2 (which, we believe, is the most important result of our paper) is still valid as we estimate the PDF uncertainties within the MSTW set and our conclusion, that the theoretical uncertainty on the $gg \to H$ cross section at the Tevatron is $\approx$ 40%, still holds true.

[11] We thank Graham Watt for pointing out to us that his calculation of the $gg \to H$ cross section with HERAPDF does not lead to such a large difference.

Nevertheless, the interpretation of the CDF/D0 limit when lowering the normalisation of the cross section, has to be modified. Instead of lowering the normalisation by 40%, one has to lower it by 30% which is the difference betweeen the MSTW and ABKM predictions. The luminosity needed by the CDF experiment to recover the present sensitivity is shown in Fig. 5 in this case. With this normalisation and including the 10% uncertainty on the backgroud rate, the needed luminosity to recover the present sensitivity will be slightly less than a factor of two.

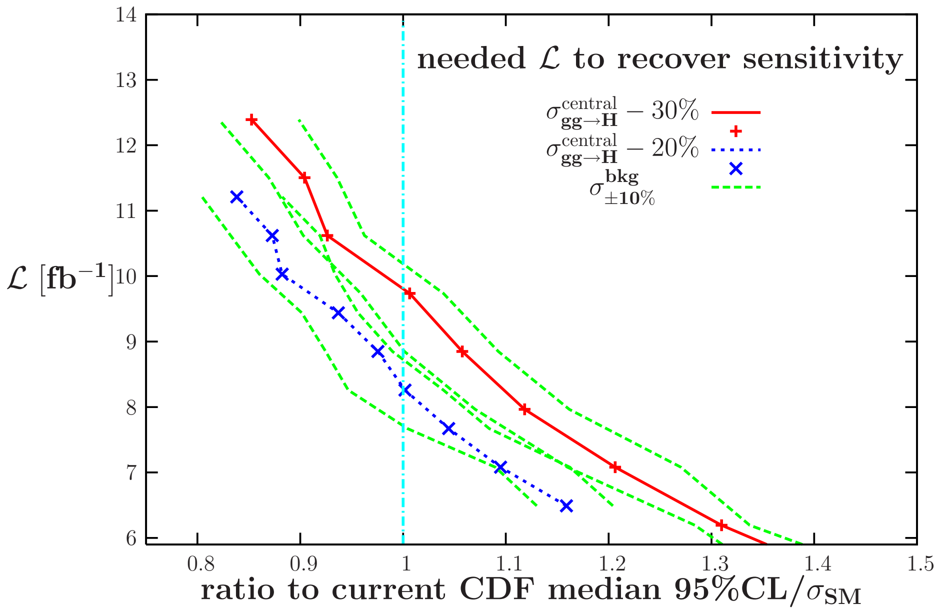

Figure 5: The luminosity needed by the CDF experiment to recover the current sensitivity (with 5.9 fb^{-1} data) when the $gg \to H \to \ell\ell\nu\nu$ signal rate is lowered by 20 and 30% and with a $\pm 10\%$ change in the $p\bar{p} \to WW$ dominant background.

Note, however, that the updated results given by the CDF/D0 experiments for the winter 2011 conferences with a luminosity of 7.1 fb^{-1} for CDF, lead to an exclusion limit that is slightly worse than the one quoted here and only the range $M_H = 158$–173 GeV is excluded. Thus, even for a 30% reduction of the production cross section only instead of the 40% used earlier, one still needs ≈ 13 fb^{-1} data to recover the sensitivity obtained with 7.1 fb^{-1}.

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